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Patents Act 1990

PROVISIONAL SPECIFICATION

for the invention entitled:

"Interferometer Control and Laser Frequency Locking"

The invention is described in the following statement:

INTERFEROMETER CONTROL AND LASER FREQUENCY LOCKING

This invention relates to a method for producing an error signal for the sensing and control of optical interferometers.

Interferometer sensing and control is required for a broad range of scientific and industrial applications. Examples include the frequency stabilisation of diode lasers for fibre optic communication systems, CW wavelength conversion for use in laser printing and photolithographic processes, coherent LIDAR, laser based gyroscope position measuring, remote vibrometry and displacement sensing. The most common approach relies on phase modulation (PM) of the incident laser beam. For multiple beam interferometers, such as the Fabry-Perot interferometer, the Pound-Drever-Hall (PDH) technique is commonly used. This technique has been utilised over the last two decades and when used with high finesse cavities is capable of achieving sub-hertz laser line widths. The PDH modulation frequency is chosen so that the sidebands are non resonant in the cavity when the carrier field is near resonance. The sidebands are reflected from the cavity with essentially no phase shift. The carrier however is near resonance and experiences the full dispersion of the cavity resonance upon reflection. The respective phase shift between the carrier and the sidebands changes the PM symmetry of the incident field introducing some component of amplitude modulation (AM) to the reflected field. As the laser frequency passes through resonance the sign of the AM changes resulting in a zero crossing error signal when the reflected field is detected and demodulated. There are several inherent disadvantages with this PM modulation technique. Firstly the implementation of this technique is complex and expensive. Additionally parasitic AM from the electro-optic modulator can cause significant locking error to occur at time scales of several seconds and longer. The error signal produced at the demodulator output is also typically quite small and consequently the system requires a large gain. Additionally, the small error signal makes the system susceptible to low frequency electronic noise generated within the servo controller for laser frequency.

The present invention proceeds from the recognition that a misaligned mode of an interferometer can be used to act as a phase reference for the correctly aligned fundamental mode of the interferometer. The interference between these two modes is capable of producing an error signal indicative of the imaginary component of the correctly aligned fundamental mode.

In the case of a two beam interferometer, including, but not limited to, a Michelson, Sagnac or Mach-Zehnder interferometer, this error signal is indicative of the phase difference of the two beams, thus allowing the sensing and control of the length difference of the interferometer paths. In the case of a multiple beam interferometer, such as a Fabry-Perot interferometer, this error signal is indicative of the difference between the fundamental mode frequency and the interferometer resonance frequency thus allowing control of the laser frequency with respect to the interferometer resonance frequency.

Accordingly, in one aspect this invention provides a method for frequency locking a laser to an optical cavity including the steps of introducing a misalignment in the incident laser radiation to the cavity to produce oscillation in the cavity of a fundamental mode and the reflection of at least one higher order mode, and detecting at least two spatially distinct portions of a single beam reflected from the cavity to produce two signals each indicative of the respective interference of the two correspondingly spatially distinct portions of the fundamental mode with two correspondingly spatially distinct portions of higher order modes of the beam, and producing an error signal indicative of the difference between the fundamental mode frequency and the cavity resonance frequency from the two signals.

In another aspect, this invention provides a method for sensing and controlling a two beam interferometer such that the relative path length of the two beams is fixed, including the steps of introducing a misalignment between the two beams to produce a fundamental mode and at least one higher order mode, detecting two spatially

distinct portions of a single beam directed from the interferometer to produce two signals each indicative of the interference of the two correspondingly spatially distinct portions of the fundamental mode with two correspondingly spatially distinct portions of higher order modes of the beam, and producing an error signal indicative of the path length difference for the fundamental modes from the two signals.

Preferably the higher order modes include the TEM01 mode. It is still further preferred that the misalignment of the incident radiation produces substantially only the TEM00 mode and the TEM01.

The two spatially distinct portions of the beam that are detected are preferably of equal size. More preferably each form about one half of the cross section of the beam. In the preferred form of the invention the detector is a single entity split into two detecting portions that provide separate outputs.

Preferably the misalignment is generated by tilt or angling the beams. However, it may be more convenient in some interferometer configurations to utilise offset misalignment. *Offset misalignment can produce an identical error signal to that* produced from tilt misalignment by situating a lens in front of the photodetector. The lens is positioned relative to the detector in such a way that beam offset at the interferometer output is converted into beam tilt at the photodetector.

In the preferred form of the invention the two signals can be directly electronically subtracted to directly provide the error signal.

It will be apparent that the error signal generated in accordance with this invention is used to drive either interferometer control or laser frequency control in the known manner.

It will also be apparent that in the case of a multiple beam interferometer in common

with the PDH system the method of the present invention utilises a non-resonant field as a phase reference however the field is generated not by modulation but by a simple misalignment of the incident field.

One embodiment of the invention will now be described by way of example of a multiple beam interferometer using tilt misalignment (tilt locking) with reference to the accompanying drawings in which:

Figure 1(a) illustrates the magnitude of the transverse electric field of the TEM00 and TEM01 interferometer modes;

~~**Figure 1(b)** diagrammatically illustrates the intensity distributions of the TEM00 (dark~~ circle) and TEM01 (light ellipses) impinging on a split photo detector;

Figure 1(c) illustrates the vector summation of electric fields for the two halves of a split detector with the TEM00 mode on resonance;

Figure 1(d) illustrates the vector summation of electric fields for the two halves of a split detector with the TEM00 mode slightly off resonance;

Figure 2(a) is a schematic representation of frequency locking system according to a first embodiment of this invention;

Figure 2(b) is a schematic representation of a frequency locking system according to a second embodiment of this invention;

Figure 3 is a graphical representation of the power and error signals for laser systems (a) with a frequency locking system according to the first embodiment of the invention, (b) with the frequency locking system according to the second embodiment of this invention and (c) with a frequency locking system according to the prior art PDH technique;

Figure 4(a) graphically illustrates respective error signal frequency spectra for prior art PDH frequency locking (top trace) and the frequency locking system according to the second embodiment of this invention (lower trace);

Figur 4(b) graphically illustrates the laser intensity noise over the same frequency range;

Figure 5 graphically illustrates laser power transmission from fluctuations measured over 50 seconds for a laser (a) using a frequency locking system according to the second embodiment of this invention and (b) using prior art PDH frequency locking; **Figure 5(c)** graphically illustrates parasitic amplitude modulation at the mixer output of a PDH frequency locking system.

It will be appreciated that in one application the present invention relates to a laser system that utilises a passive optical cavity of selected resonant frequency as the means of providing frequency stabilization. As indicated above systems of this type are generally known and share the common feature of the generation of an error signal representative of the deviation of the laser output from the resonant frequency of the cavity which is used to drive frequency control of the laser. The known components of this system do not form part of the present invention and therefore will not be described in further detail.

The present invention utilizes a non-resonant field generated by misalignment of the incident field as a phase reference. In general a cavity breaks down a misaligned input field into spatially distinct Hermite-Gauss cavity modes. Higher order Hermite-Gauss modes experience different Gouy phase shifts and thus have different resonant frequencies. For tilt locking the input beam is aligned and mode matched to give only the TEM00 (fundamental) mode and the TEM01 (misalignment) mode. The transverse electric field distribution for both modes is shown in Fig. 1(a). The TEM01 mode has a double hump intensity distribution whilst the TEM00 mode exhibits a simple Gaussian intensity profile. The reflected beam is detected on a two element split photodetector as shown in Fig. 1(b) in such a way that each hump of the TEM01 mode falls in a separate half of the photodetector. The split detector allows the interference between the fundamental TEM00 mode and each individual TEM01 mode hump to be measured separately. The TEM01 mode arises from two types of misalignment: beam displacement and beam tilt. Beam displacement produces a TEM01 higher order mode which has a zero phase shift in one half plane and a π phase shift in the other.

Beam tilt however produces a TEM01 mode which has π/2 phase shift in one half plane and a -π/2 in the other. *Figure 1(c) shows the corresponding electric field vector* addition of the TEM00 and tilt TEM01 modes on the two halves of the photodetector when there is no phase shift added by the cavity. This corresponds to the TEM00 mode being exactly resonant with the cavity and the TEM01 being non-resonant. On the left half the TEM01 adds to the TEM00 mode with -π/2 phase while on the right half, the TEM01 adds with +π/2 phase. The resultant vectors on both halves are then equal in magnitude. An error signal is obtained by subtracting the outputs from the two halves of the photodetector which in this case gives zero. As the carrier drifts slightly away from resonance, the TEM00 mode acquires an equal phase shift in both photodetector halves while the non-resonant TEM01 mode remains unchanged as shown in Fig. 1(d). This causes the resultant vector sum in one photodiode half to grow whilst the other shrinks. The electronically subtracted error signal is now non zero and is proportional to the phase shift of the TEM00 fundamental mode.

Figures 2(a) and 2(b) show two experimental arrangements using the locking technique of this invention. The first, shown in Fig. 2(a), obtains the error signal as described above by measuring the light directly reflected from the cavity with a slightly tilted input beam. Figure 2(b) shows double pass tilt locking, where the light passes through the cavity once and is then retro-reflected, with a slight tilt, back through the cavity. The beam reflected on this second pass is used to obtain the error signal.

The arrangement shown in Fig. 2(a) suffers from the constraint that any input beam displacement causes an offset in the zero crossing point of the error signal. The double pass configuration of Fig. 2(b) minimizes this problem by using the first pass through the cavity to spatially filter all higher order modes. In addition the beam path from the retro-reflector to the split detector can be made extremely short and mechanically stable.

The split photodetector uses a commercially available quadrant photodiode with the

two quarters of each half added together. This forms a vertically split two element detector requiring a horizontal tilt to extract the error signal. The photodetector has both sum and difference outputs allowing both the power and error signal to be monitored independently.

Figure 3 shows experimental results as the cavity length is scanned using a PZT attached to one of the cavity mirrors. Figure 3(a) shows the reflected power and error signal obtained using the single pass locking scheme of Figure 2(a)as the cavity is scanned through a complete free spectral range (FSR). A large error signal (5V p-p) is obtained even with an extremely small misalignment (TEM01/TEM00~ 1%). In Fig. 3(a) an error signal also appears as the small TEM01 mode passes through resonance with the fundamental now acting as a phase reference. As both these error signals result from the TEM00-TEM01 product they are both the same size, even though the TEM01 error signal has negligible light inside the cavity.

Figure 3(b) shows the same results with the double pass locking scheme of Figure 2(b). Due to the mode cleaner action of the first cavity pass, there is no error signal at the TEM01 resonance. In addition, the error signal drops to zero away from resonance somewhat faster than the single pass case due to the filtering effect of the first cavity pass.

For comparison Fig. 3(c) shows the transmitted power and error signal using the prior art PDH technique. The error signal is taken at the output of the demodulation mixer and demonstrates that the size of this signal (0.5V p-p) is at least an order of magnitude smaller than either of the locking techniques according to this invention. In this regard the size of the locking signal produced in accordance with the invention was deliberately reduced to allow use of the same frequency servo designed for PDH locking. Locking error signals of 25V p-p are readily achieved simply by increasing the beam tilt. This is technically difficult to achieve using the PDH technique due to the demodulation process.

A well known feature of the PDH technique is its immunity to laser intensity noise. In order to verify similar immunity for this invention the frequency spectrum of the error signals of both techniques were compared. Figure 4(a) shows the experimentally obtained frequency spectrum of the error signals from both PDH and single pass locking. The noise features shown on the PDH error signal are typical of the 50 mW Nd:YAG laser (Lightwave model 120) used in the experiments. The same features are clearly present on the locking error signal according to this invention (this spectrum is modified slightly by the photodetector frequency response rolling off at approximately 400kHz). The intensity noise spectrum of the laser used, shown in Fig. 4(b), has a large single feature at 430 kHz; the laser relaxation oscillation. This feature is absent ~~from both error signals indicating immeasurable intensity noise cross coupling for both~~ PDH and locking according to this invention.

The locking system of this invention relies on two factors to achieve this intensity noise immunity: initial balancing of power on each half of the photodiode, and DC gain of the frequency servo. Balancing the power allows the subtracter circuit to remove laser intensity noise (down to the shot noise limit). However, even if the power is slightly imbalanced, the servo will adjust the lock position to recover power balance and thus intensity noise immunity. For both results in Fig. 4(a) the servo had a low frequency gain of greater than 100dB.

One of the benefits of the present invention is the potential for excellent long term stability. Figure 5 plots the transmitted power for both double pass locking and PDH locking over a period of 50 seconds. Figure 5(a) shows the fluctuations of the power transmitted through a high finesse (f=4000) cavity using double pass locking. As can be seen, there is ≈ 0.1% change in power over this time scale. This drift is most likely due to drift in the output power of the laser. Figure 5(b) shows the same measurement using the PDH system to lock the laser to the cavity. Over the same period the PDH system exhibits ≈ 0.3% transmitted power fluctuation, with considerably greater short term (~5 seconds) variation. The increased fluctuations are probably due to parasitic

AM caused by temperature variations in the resonant phase modulator (New Focus model 4003). Figure 5(c) shows the mixer output with the cavity blocked, giving an indication of the variation of parasitic AM over 50 seconds. From these power measurements it is clear that the locking system of this invention produced significantly less locking error over these time scales.

It will be apparent that the frequency locking system of this invention is a simple and inexpensive system requiring only a quadrant photodiode and several low frequency op-amps. This scheme provides excellent long term stability limited only by mechanical stability of the mirror/cavity/detector beam path. Mechanical stability of ~~these components can be optimized by mounting all three elements on a single rigid~~ spacer. Long term stability is further improved due to the large error signal size, rendering servo noise and laser frequency drift insignificant. This combination of low cost, simplicity and excellent stability facilitates the use of misalignment locking in a broad range of applications.

The method of this invention is not restricted to optical cavities and can be applied to two beam interferometers. Figure 6(a) shows a schematic of misalignment locking being applied to a Mach-Zehnder interferometer. The Mach-Zehnder is aligned in such a way that the two interfering beams experience a relative tilt. When operating around a dark fringe the subtraction from the two halves of the photodiode again yields a signal which is indicative of the imaginary component of the correctly aligned beam components.

Figure 6(b) shows an alternative arrangement whereby a Sagnac interferometer is aligned such that the interfering beams have a relative offset error upon recombination. A lens is used to convert this offset to tilt at a photodetector positioned at the focal plane of the lens. The subtracted output of the photodiode can be used as a sensitive signal readout for the Sagnac interferometer.

Figure 6(c) shows experimental results for the Mach-Zehnder configuration of figure 6(a). The two traces plotted are the total power detected and error signal, both measured by the same split photodiode. The subtracted photodetector output provides a zero crossing error signal at minimum and maximum fringe powers. Hence the interferometer can be locked to either a bright or dark fringe.

The foregoing describes only some embodiments of the invention and modifications can be made without departing from the scope of the invention.

~~DATED this 30th day of June, 1999~~
THE AUSTRALIAN NATIONAL UNIVERSTY
by its Patent Attorneys
DAVIES COLLISON CAVE

FIGURE 1

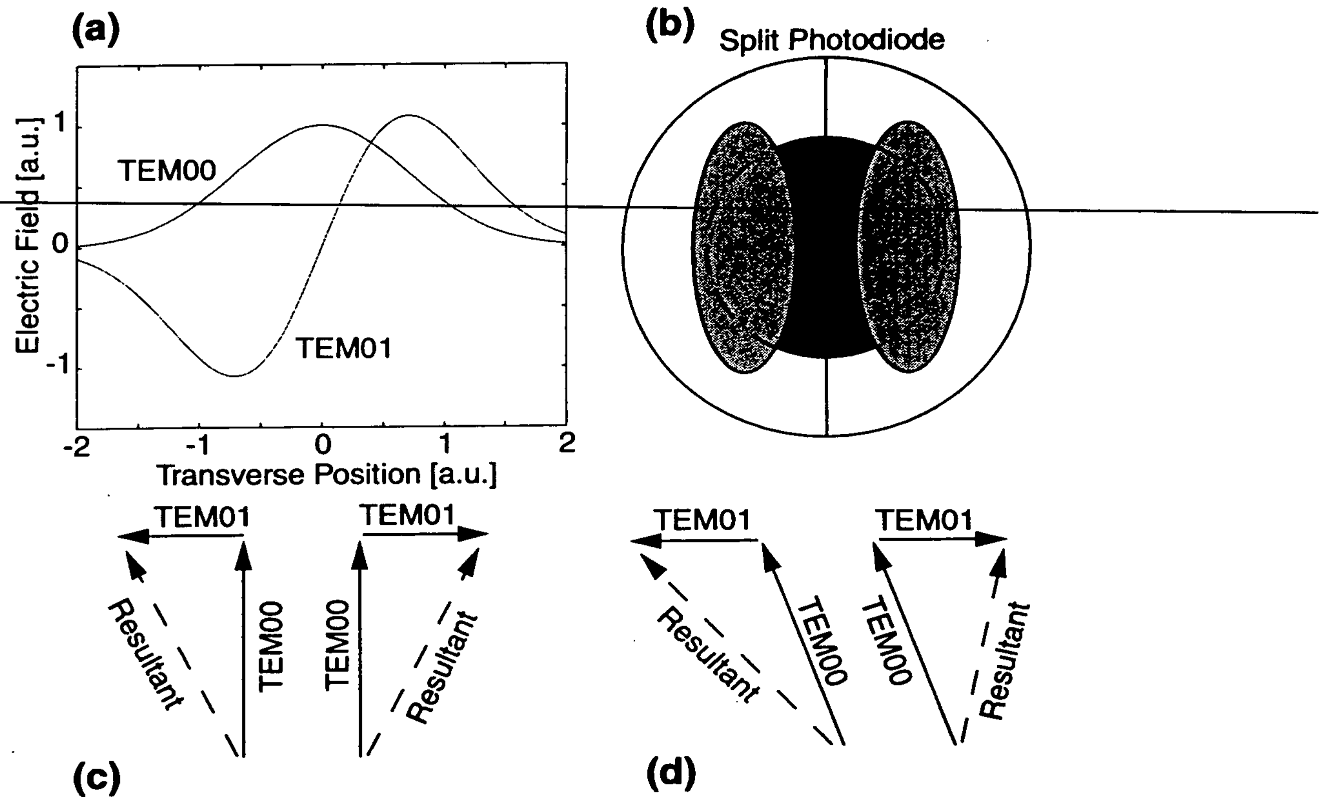
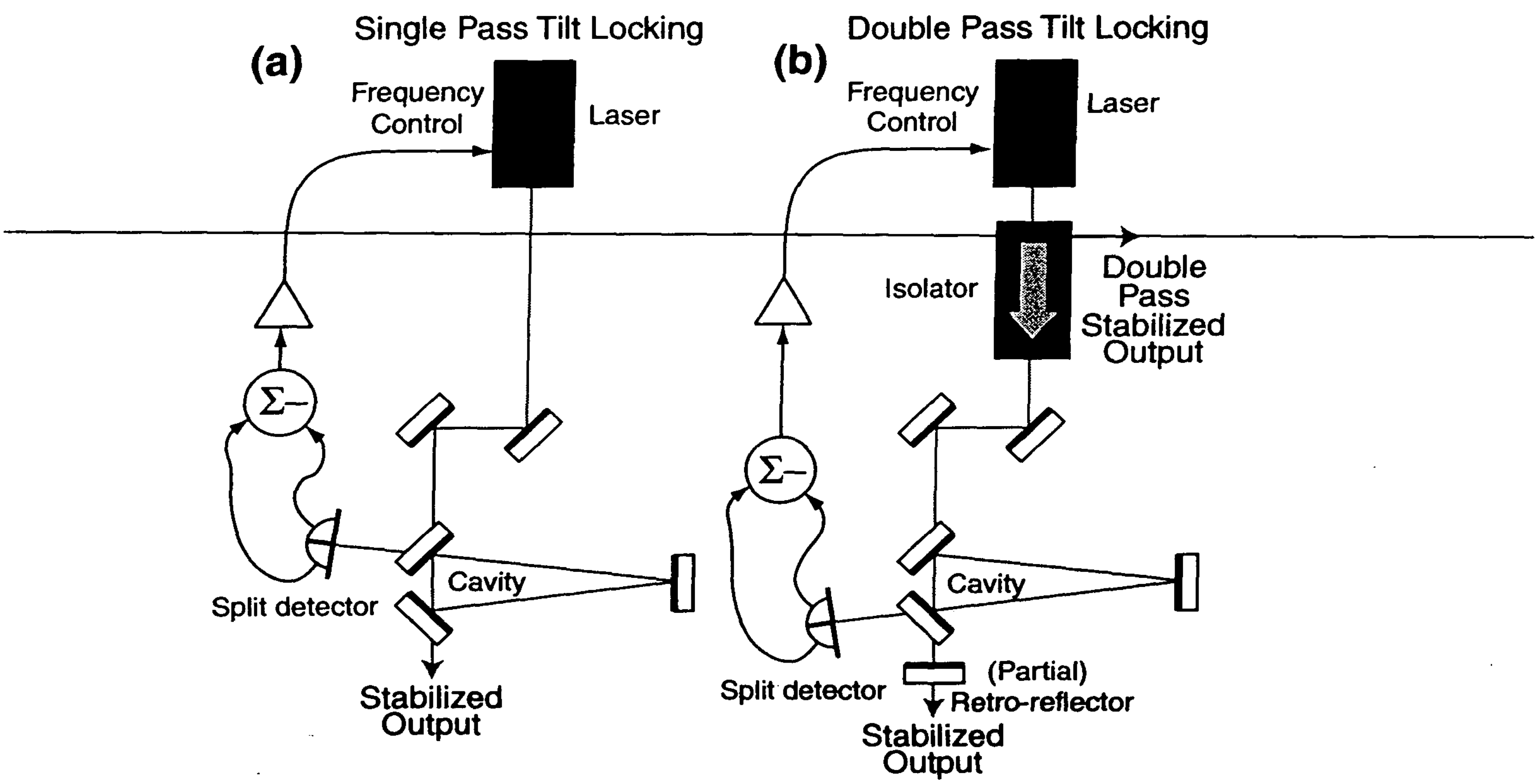
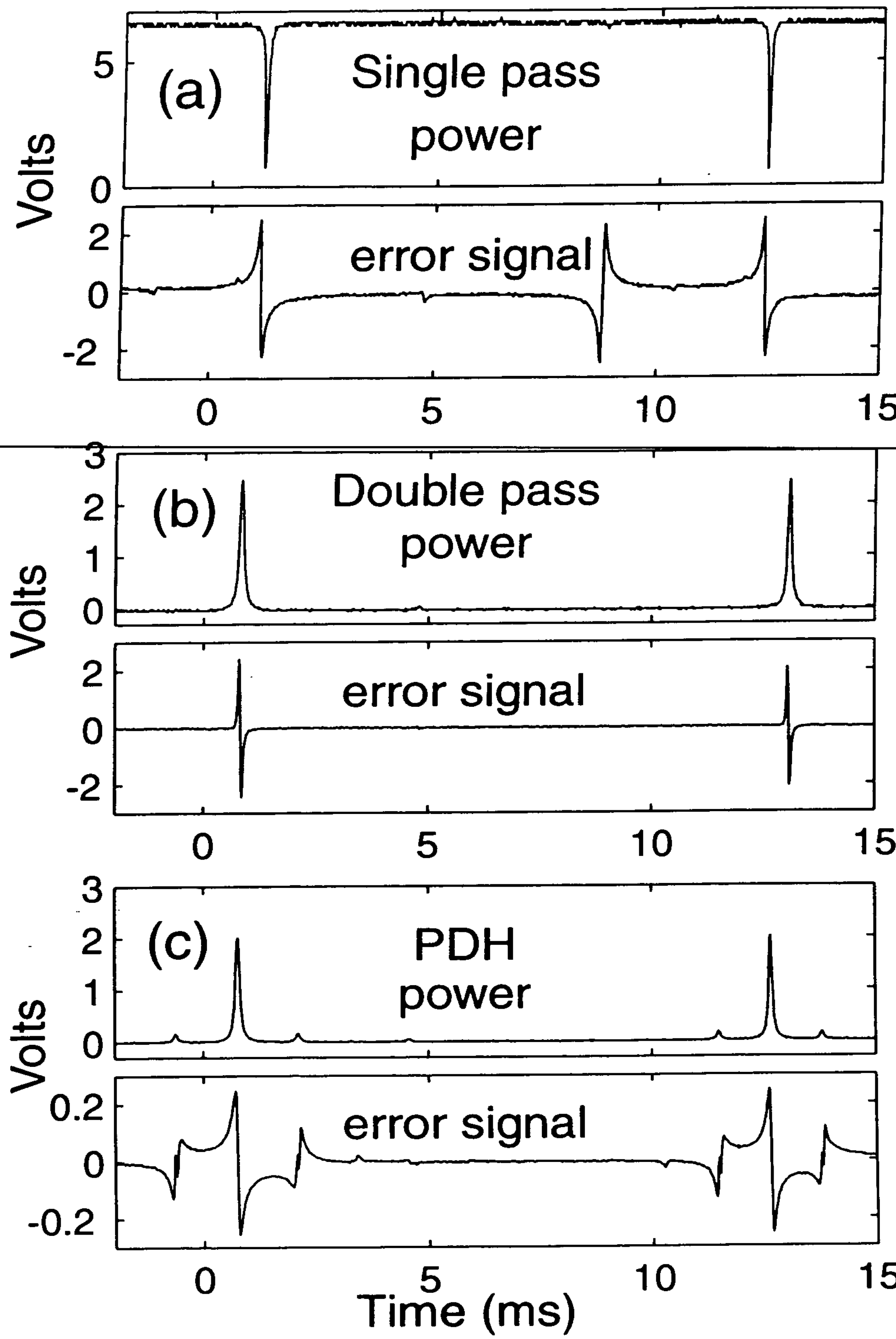

(a)
(b)
Split Photodiode
Electric Field [a.u.]
Transverse Position [a.u.]
TEM00
TEM01
1
0
-1
-2
-1
0
1
2
TEM01
TEM01
TEM00
TEM00
Resultant
Resultant
TEM01
TEM01
TEM00
TEM00
Resultant
Resultant
(c)
(d)

FIGURE 2



Single Pass Tilt Locking
(a)
Frequency Control
Laser
Split detector
Cavity
Stabilized Output
Double Pass Tilt Locking
(b)
Frequency Control
Laser
Isolator
Double Pass Stabilized Output
Cavity
Split detector
(Partial) Retro-reflector
Stabilized Output

FIGURE 3



(a)
Single pass power
error signal
(b)
Double pass power
error signal
(c)
PDH power
error signal
Volts
Time (ms)

FIGURE 4

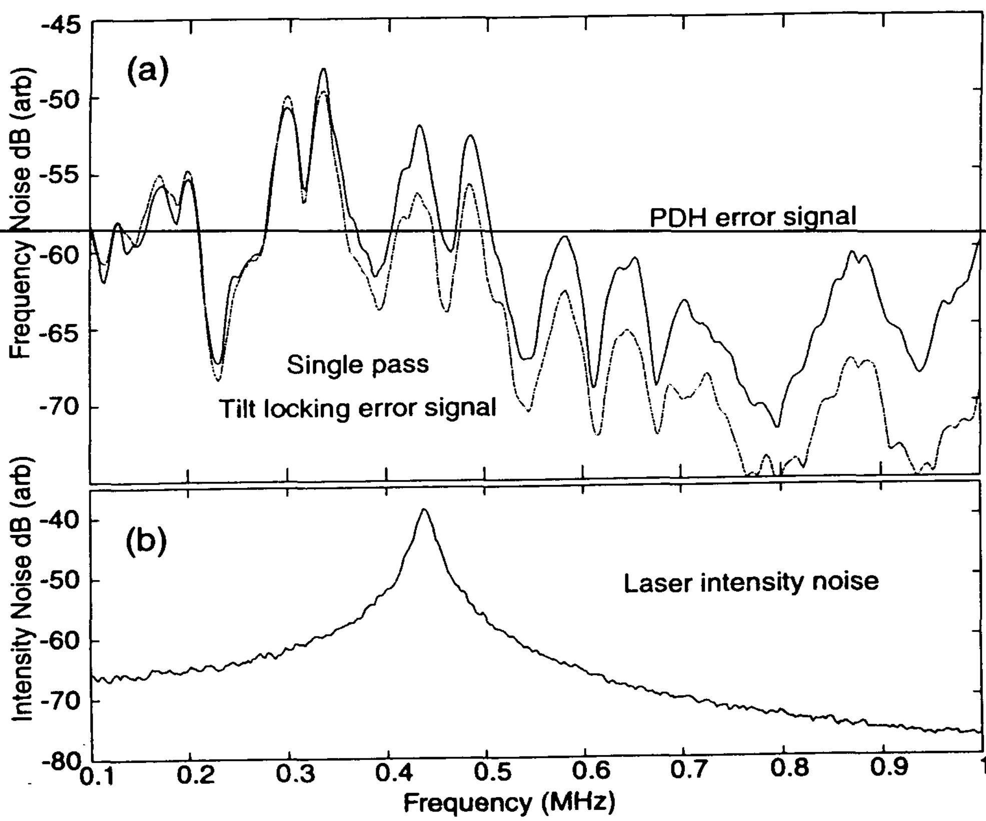
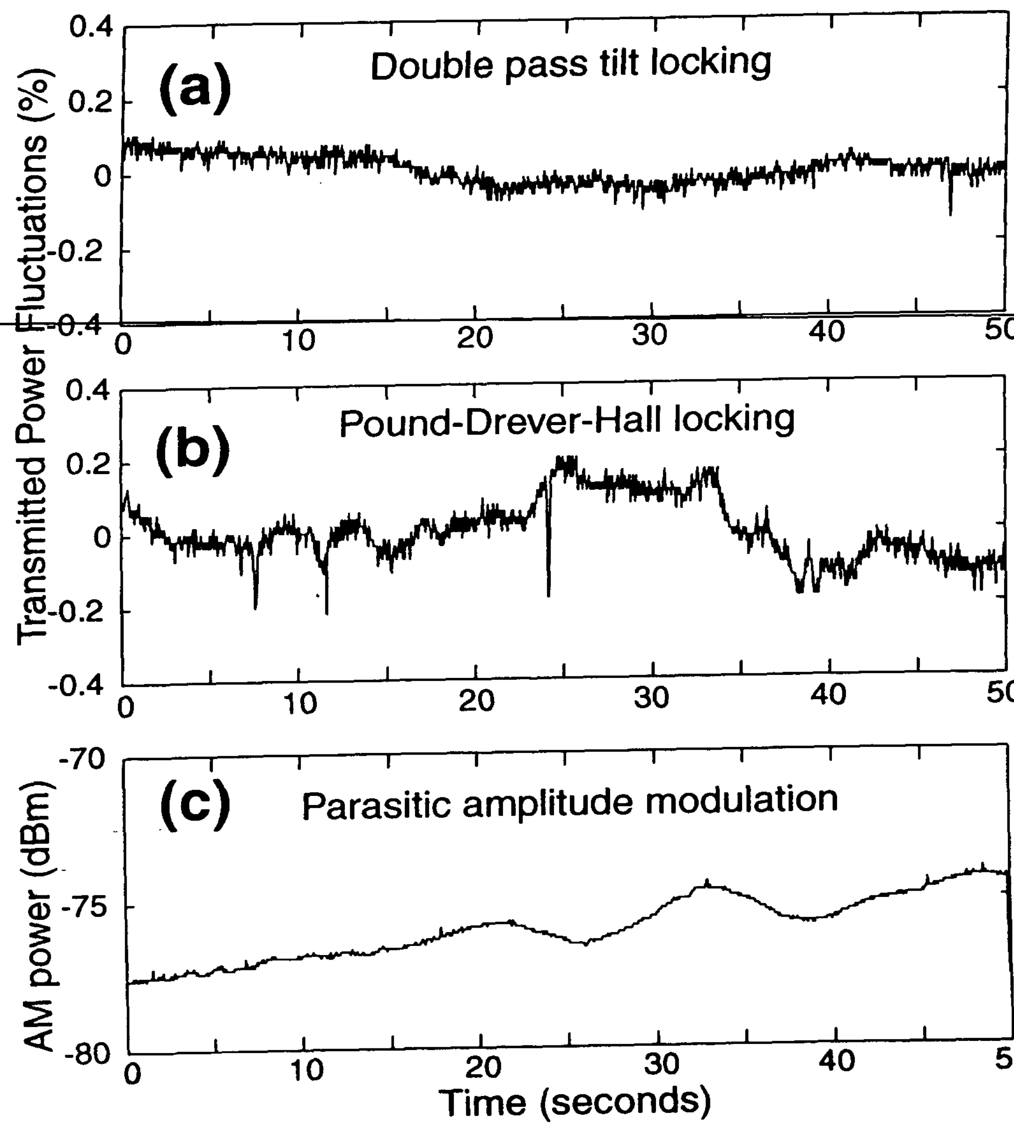
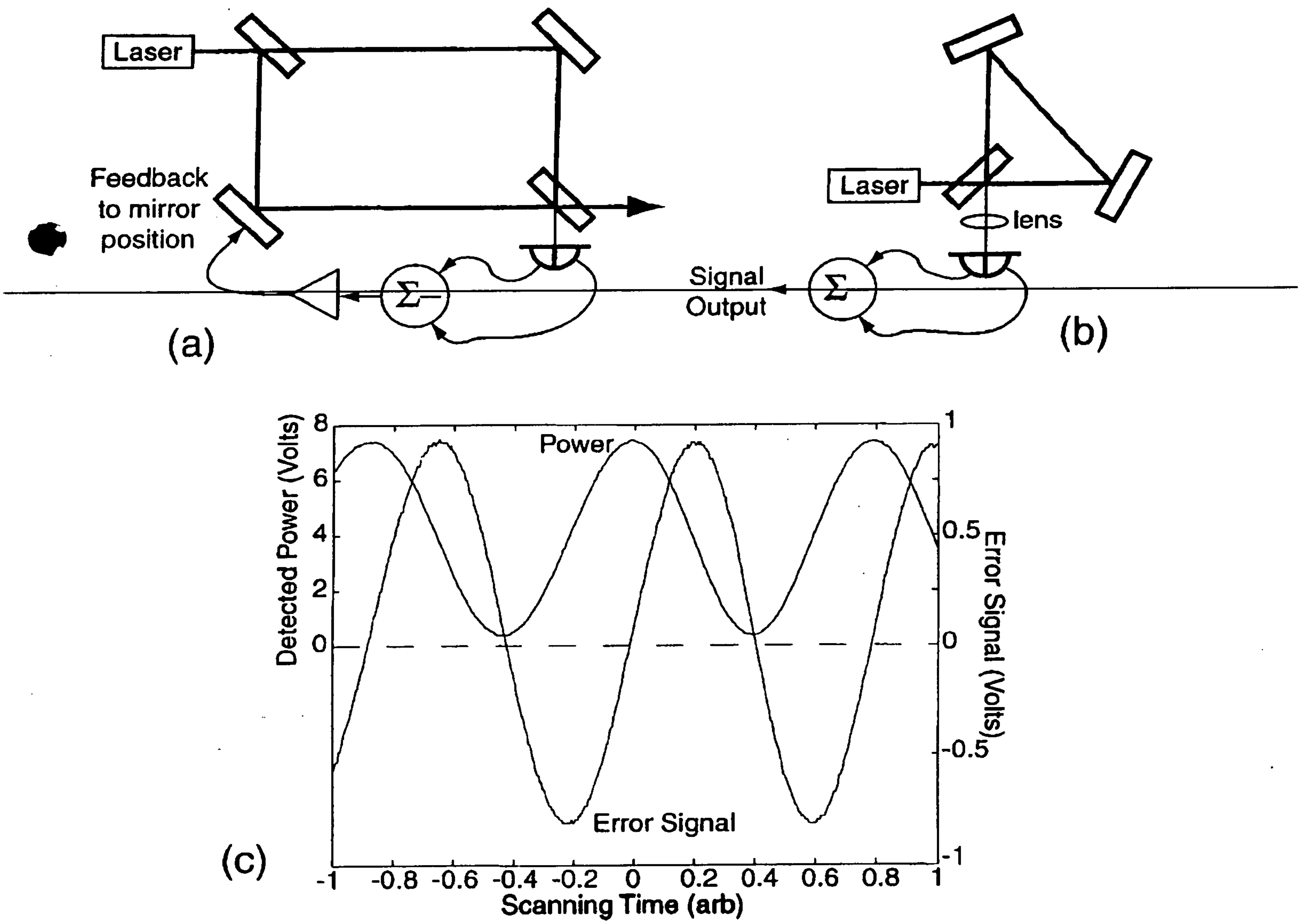

(a)
(b)
PDH error signal
Single pass
Tilt locking error signal
Laser intensity noise
Frequency Noise dB (arb)
Intensity Noise dB (arb)
Frequency (MHz)
-45
-50
-55
-60
-65
-70
-40
-50
-60
-70
-80
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

FIGURE 5



(a)
Double pass tilt locking
(b)
Pound-Drever-Hall locking
Transmitted Power Fluctuations (%)
0.4
0.2
0
-0.2
-0.4
0
10
20
30
40
50
(c)
Parasitic amplitude modulation
AM power (dBm)
-70
-75
-80
Time (seconds)

FIGURE 6



Laser
Feedback to mirror position
(a)
Laser
lens
Signal Output
(b)
Power
Error Signal
Detected Power (Volts)
Error Signal (Volts)
Scanning Time (arb)
(c)